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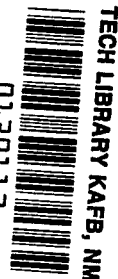


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by David A. Stewart and Robert E. Dannenberg

*Ames Research Center
Moffett Field, Calif.*

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D.





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SUMMARY

The problem of operating a large combustion driver is principally that of obtaining detonation-free combustion. Certain factors that influence the performance of a wire ignition system and the consistency in the initiation of the combustion process are described. These factors are based on operating experience with a large volume driver at the Ames Research Center of NASA. A semiempirical method which describes the physical reaction of the wires and provides a correlation between the electrical and thermodynamic energy necessary to melt the wires is presented. It is shown that wire melting, not exploding, is required for detonation-free combustion in a large driver chamber.

INTRODUCTION

The shock-driven wind tunnel has been used widely as a basic research tool in high-energy gasdynamics. It is generally understood that the performance of such a device can be substantially enhanced by increasing the acoustic velocity of the driver gas, by increasing the pressure of the driver gas, and by making the driver-to-driven-tube area ratio large. Likewise, it is generally accepted that the available test time is directly related to the length of the driver in many cases and, therefore, relatively long driver sections are often desirable. It is not so generally recognized that driver volume can be used to increase the available test time. Reference 1 presents the theoretical basis for this concept, as well as an experimental application of a large volume heated driver, and shows that it is practical, and reasonably economical, to obtain a relatively high-temperature, high-pressure driver gas in a large volume chamber. The combustion gas mixture is hydrogen and oxygen in about 80-percent helium. A more recent study of the shock-tunnel performance is reported in references 2 and 3.

One of the attendant problems in using a large volume combustion driver is that of obtaining smooth burning so that the possibility of damage from a large detonation may be avoided. In general, the onset of detonation is characterized by a pronounced increase in the rate of pressure rise in a combustion cycle. A review of early experience in the 1-foot shock tunnel indicates that one out of eight combustion cycles was close to detonation. The few times detonation did occur, it caused considerable damage to internal parts, subjected the chamber to high stresses, and resulted in the loss of test data. An investigation was initiated, therefore, to determine the critical parameters relating to the ignition and burning of a gaseous mixture.

The present paper presents the results of this investigation as well as a first-order approximation for predicting values of the electrical parameters for proper ignition.

SYMBOLS

C	capacitance
d	diameter
I	current in individual ignition wire
k	arbitrary positive constant denoting the initial and final current ratios
K_{AC}	action integral constant
l	length of ignition wire
L	inductance
n	number of wires
R	universal gas constant
R_c	critical resistance of ignition circuit
R_L	load resistance (ignition wires)
S	cross-section area of a wire
T	temperature
t	time
t_R	reaction time for wire melting process
V	voltage
W_T	thermal energy necessary to completely melt the wire

Subscripts

f	final value
o	initial value

TEST EQUIPMENT

The tests were conducted in two gaseous environments: a hydrogen-oxygen-helium combustion mixture and atmospheric air. The tests with the combustible mixture were performed in the combustion chamber of the Ames 1-foot shock tunnel. The tests with air (heated-wire studies only) were performed in the combustion chamber, in a full-length multiple-wire test jig and in a smaller single-wire test jig. Current and voltage traces were recorded on oscilloscopes during all tests. In addition, during the tests in the combustion environment, pressure traces were taken on an oscilloscope as well as on a high-speed oscillograph. Consider first the configuration of the wire and the energy system associated with the combustion chamber.

The combustion driver of the Ames 1-foot shock tunnel is shown in figure 1. Its internal dimensions are 27 inches in diameter by 25 feet in length. The driver gas, helium, is heated by the combustion of oxygen and hydrogen to a temperature of 4200° F and to a pressure of about 5200 psia from an initial pressure of 750 psia. The initial gas volume consists of approximately 7-percent oxygen, 12-percent hydrogen, and 81-percent helium. Combustion is initiated by electrically heating and melting wires with a discharge of energy from a 10-kilojoule capacitor bank. The ignition-wire assembly consists of six (0.0031-inch diameter) Manganin wires stretched along the length of the chamber as indicated in figure 2. The wires are connected in parallel and are strung concentric with the axis of the chamber. At one end of the chamber the parallel wire assembly is attached to a 10-inch-diameter ring which, in turn, is grounded through the chamber wall. At the high-potential end, the wires are connected to mechanical fingers which are insulated from the combustion-chamber walls. Two ground leads, one at each end of the 24-foot chamber, insure a definite chamber ground connection during the discharge of the capacitor bank. A schematic diagram of the capacitor discharge network is shown in figure 3.

The multiple-wire test jig is shown in figure 4. The wires were positioned in an arrangement geometrically similar to that used in the combustion chamber. This jig was located adjacent to the combustion chamber so that the tunnel energy storage system could be used. The wires were strung between the two copper plates and secured by brass screws. The wires were heated by electrical discharges at initial voltages from 10 to 23 kV, with a fixed capacitance of 52 μ f. Wire residue was inspected visually after each test. High-speed motion pictures, at a framing rate of 8000 per second, were taken of the heating process at one initial voltage.

The circuit arrangement of the single-wire test jig was similar to that of the multiple-wire jig. The wire holder was mounted on an adjustable insulated rail, which permitted the wire length to be varied from 0.5 to 2.5 feet. A 0- to 10-kV regulated power supply was used to charge the capacitors and an arc gap was used to isolate and regulate the voltage to the wire. Tests were conducted with storage capacitors of 4 and 6 μ f over a range of initial voltage settings from 1 to 4.5 kV. With the 4- μ f storage capacitor, test time constants were 0.06, 0.125, and 0.300 msec, which involved wire lengths from

0.5 to 2.5 feet. With the 6- μ f storage capacitor, wire lengths of 0.7 and 1.67 feet were used for time constants of 0.125 and 0.300 msec.

RESULTS AND DISCUSSION

A number of factors can influence the processes in the combustion chamber of the 1-foot shock tunnel so as to cause detonation. These include uniformity of the gas mixture, flame-path length, and the thermoelectric behavior of the ignition system. A study of the existing literature indicated that the thermoelectric process was perhaps the most difficult of these to define, yet it could be the primary cause of detonation. The experiments were thus directed toward understanding this aspect of the ignition phenomenon.

Wire Configuration Considerations

The combustion process is essentially independent of the thermoelectric behavior of an ignition source once a self-propagating flame front is established (see, e.g., ref. 4). However, prior to this time the physical properties of the wire and the method used to heat the wire can influence the type of flame front that will be formed. In turn, the uniformity with which chemical reaction energy contained in the thin gaseous layer next to the wire is released will also influence the smoothness of the combustion process. Three conditions which must be met in order to establish proper combustion are: First, for geometric reasons, the wire must be heated uniformly along its length in order to establish a continuous cylindrical flame front; second, the ignition wires must be spaced so that the flame path length between adjacent wires and the wall does not exceed approximately 1 foot (The effect of flame-path length on detonation has been discussed in refs. 1 and 5.); and third, the melting temperature of the wire material (2320° R for Manganin) must be greater than the critical ignition temperature of the gaseous mixture. The critical ignition temperature is the lowest temperature of the combustible gas mixture (in its environment) at which a self-propagating chemical reaction will occur; for the combustible mixture it is estimated to be about 1640° R.

The type of wire material does not play a primary role in the ignition process, provided it is homogeneous and noncatalytic. The wire need only provide sufficient surface area and be heated to a temperature in excess of the critical value (see refs. 4 and 6). The time for wire heating is not clearly defined in this application, although intuitively it should be very short compared to the over-all flame propagation time. It has also been indicated to be a function of the energy of the ignition source. In a qualitative sense, if the wire is to establish a relatively uniform cylindrical flame front, it must be heated above the critical temperature over the entire length quickly enough that preignition at local "hot spots" will not distort the front significantly.

An equation was developed in reference 4 which relates the thermal properties of the gas and the minimum wire diameter necessary for achieving the

critical temperature and the resulting self-propagating combustion. The equation for the wire diameter is

$$d = \sqrt{\frac{2\lambda(T_s - T_o)^2 E}{qW(T_s)RT_s^2}} \quad (1)$$

where T_o is the initial temperature of the gas mixture, T_s the critical ignition temperature of the gas mixture, λ the thermal conductivity of hydrogen, E the activation energy of hydrogen per mole, q the heat of reaction, and $W(T_s)$ the rate of chemical reaction. The calculated minimum wire diameter was 0.0022 inch for the conditions in the 1-foot shock tunnel (i.e., the pressure is constant, the temperature is adiabatic, and the reacting gases are in stoichiometric proportions during the subcritical period). The diameter of the wire used is 0.0031 inch.

Melting Wire Study

The multiple-wire test jig was used for determining the melting characteristics of the ignition wires for initial capacitor voltages from 10 to 23 kV for the present system. The results indicated three types of wire melting. In the range from 10 to 15.5 kV, the residue consisted of wire segments about 1 to 1-1/2 inches long as shown in figure 5(a) indicating that in this range, the melting was not uniform but occurred at random locations along the wire. Calculations show that the energy discharged was not sufficient to heat the complete wire to its melting temperature. In the voltage range from 16 to 17.5 kV the wire residue consisted of small spherical beads as shown in figure 5(b), indicating that the melting was uniform over the complete length of the wire. In the highest voltage range, 18 to 23 kV, the discharge of the energy through the wire was accompanied by a loud "bang" and the wire residue was widely scattered, indicating that an explosion had occurred. The onset of vaporization, perhaps at localized centers, is a phenomenon normally associated with the "exploding wire" process. It appeared that for the particular test setup there was a range of voltages in which the melting of the wire was compatible with good ignition, namely, the range from 16 to 17.5 kV where uniform melting occurred.

The test at 17 kV was repeated so that high-speed motion pictures could be taken. Selected pictures from this test which show the condition of the wire during various stages of the melting process are presented in figure 6. (The camera was positioned such that the six wires are aligned in groups of two.) The current history corresponding to the pictures is presented in figure 7, with time identification to permit correlation with figure 6. Luminosity was first recorded on the film at approximately 0.250 msec after the current was applied to the wires. It is surmised that at 0.375 msec localized melting is occurring along the wires, which increases the resistance and inductance of the wire system. The resulting increase in the energy stored locally in the wires' magnetic field would make the Bridgeman effect (back emf)(ref. 7) an important factor in the energy transfer to the wire.

At 0.625 msec (fig. 6(d)), which corresponds to the time just ahead of the pronounced change in slope of the current trace of figure 7, the electrical input to the wire is equal to the calculated thermal energy necessary to raise the temperature of the entire wire to the start-of-melt point. This point refers to the beginning of the liquid phase. The end-of-melt point, then, is defined as the end of the liquid phase. During the transition from the beginning to the end of the liquid phase, the wire inductance and resistance increases rapidly and the current flow through the wire is reduced to zero. The last frame in the sequence (fig. 6) shows the wire in a liquid solid state approximately 0.2 msec after the current has reached zero. It is apparent, when comparing figures 6(e) and 6(f), that during the time of no current flow, the wire material has cooled to a point where only a few hot spots remain. It seems reasonable to assume, therefore, that during the cooling period the surface tension of the liquid metal is sufficient to cause the formation of liquid spheres which harden into the residue shown in figure 5(b).

The tests were repeated in the combustion chamber with the standard oxygen-hydrogen-helium gas mixture at initial capacitor voltages from 16 to 20 kV to permit correlation of the jig tests with tests under actual combustion conditions. The current traces during the capacitor discharge were essentially the same as those for the jig tests, indicating there was little effect of changing from an atmospheric to a combustion environment. The pressure data indicated that as the initial capacitor voltage was increased beyond 17.5 kV, the magnitude of the rate of pressure rise increased until, at 20 kV, the onset of detonation was evident. This is illustrated in figure 8 where the pressure variation with time is shown for combustion cycles with three initial capacitor voltage settings. It is apparent that at 17 kV the combustion was smooth. A typical combustion record is shown in figure 8(a). At 20 kV the combustion is not smooth, as demonstrated by the changes in the slope of the curve during the early stages of combustion, indicating a condition approaching detonation. Included on the figure is the pressure variation from an earlier combustion cycle for 23 kV where detonation did occur. This variation can be characterized by the double inflection in the pressure-time curve. The inflection occurred in the middle portion of the combustion process and was followed by an increase to essentially an infinite pressure-rise rate.

The agreement between the combustion tests and jig tests is very good, since the conditions that produced particle vaporization of the wires in the jig tests also produced combustion cycles which were close to detonation. The lower voltage settings were not tried in a combustion environment because the random nature of the localized melting could lead to detonation. The data from these multiple-wire tests and a study of existing literature provide a comparative basis for a method for predicting the initial current required for smooth combustion in similar applications. This method is developed in the following section.

Method of Determining Energy Requirements

In this section, a first-order approximation is given for determining the initial current and capacitance required for properly initiating a

cylindrical flame front from a wire ignition source. This method is derived from the available literature, the experimental results presented earlier for stoichiometric combustion processes, and the "action integral" as determined by Anderson and Neilson in reference 8.

It was apparent from the results of the multiple-wire jig tests that one of the major problems associated with this type of ignition (i.e., melting wire) may be related to the onset of the exploding-wire phenomenon. To avoid this problem, as well as any undesirable effects that might result from an oscillatory type of discharge, only an RC-type of capacitance discharge will be considered in this section. If the relationship $\sqrt{L/C} \ll R_L/2$ holds, then essentially an RC discharge will follow (ref. 9). The initial inductance (L) of the wire system can be calculated using the relationships for self and mutual inductances as given, for example, in reference 10. If it is assumed that R_L is constant during the discharge of the capacitor system, it follows that the equation relating current and time is of the form

$$I = I_0 e^{-(1/R_L C)t} \quad (2)$$

where $R_L C$ is the characteristic time constant of the system. This expression for current-time history is compared with experimental data in figure 9, for values of $R_L C$ from 0.06 to 5.98 msec. The results are seen to be in substantial agreement for about 3/4 of the total discharge time. Beyond this, the measured current drops quickly to zero in a manner which indicates the discharge is no longer of the simple RC type. For this analysis, the current flow at the inflection point of the experimental curve will be referred to as the final current, I_f , and the time associated with I_f is designated the reaction time, t_R .

An energy equation was developed in reference 8 which permits relating the current and the reaction time of an ignition wire. This equation has been called an "action integral" and is defined as:

$$K_{AC} = \int_0^{t_R} \frac{I^2(t)}{S^2} dt \quad \frac{\text{ampere coulomb}}{(\text{circular mils})^2} \quad (3)$$

Several values of the action integral are shown in figure 10. These values were obtained from current traces taken during the wire melting study. The action integral point derived from the current trace of figure 7 is labeled "probable end-of-melt point." It is in this area of the curve that wire ignition of the combustible gases resulted in a smooth consistent combustion curve. It should be noted that the value of the action integral is a constant for energy inputs above that required to melt the wire completely. This result has also been noted in reference 8. The action integral calculation was repeated for various time constant circuit values, using the single-wire jig, and is presented along with the above results in figure 11. The solid symbols in the figure correspond to the experimentally determined values of initial current density necessary to reach the probable end-of-melt

point for the different RC time constants used. These points indicate that the initial current density value is the minimum for which the action integral attains its constant value. In addition, the figure shows that equation (3) is valid for large variations in RC. It will be shown therefore that a semi-empirical method, in which the action integral (K_{AC}) is determined experimentally from a bench test, can be used to calculate the initial current required to melt the wire for different RC time constant circuits.

The current-time history is defined by equation (2) and with $I = I_F$ at $t = t_R$, the time constant is directly proportional to the reaction time, denoted as

$$R_L C = k t_R \quad (4)$$

where

$$k = \frac{1}{\ln(I_O/I_F)}$$

The time constant of the circuit determines the rate at which the current will decay in the wire, thus fixing the values for the minimum initial current and the final current for which the action integral will attain its constant level. The term k is used as an arbitrary constant in evaluating the current corresponding to the probable end-of-melt points. The term k can be related to the action integral and the reaction time through the current function, by substituting $k t_R$ for $R_L C$ in equation (2). With equation (2) substituted for I in equation (3), we integrate between the limits of 0 and t_R to obtain the reaction time of the wire as a function of K_{AC} and k :

$$t_R = \frac{2K_{AC}S^2}{I_O^2 k (1 - e^{-2/k})} \quad (5)$$

Equation (5) is used to map k , relating the initial- to final-current ratio, as a function of both initial current and reaction time for a particular material. This is illustrated by the long-dash lines in figure 12. The initial current and the reaction time for a wire at the probable end-of-melt point is determined in the following manner. A constant RC curve is superimposed on the constant k curves of figure 12, by using equation (4) to compute values of t_R . Then, the value of I_O for any t_R is used in equations (2) and (3) to compute K_{AC} . The procedure is continued until the lowest value of initial current is found for which the action integral is still constant. This value, considered to be the "probable end-of-melt point," is compared in figure 12 with the experimental results obtained from the single- and multiple-wire jig tests and presented earlier in figure 11. The differences between the two sets of data are attributed to effects of temperature on wire resistance and inductance and these effects become more pronounced at higher current flows. The line joining the open symbols of figure 12 labeled probable end-of-melt line is unique in that it represents all RC

circuits and wire sizes, within the limitations of the action integral concept. This line is given in a more convenient form in figure 13, which shows that for time constants greater than 0.125 msec agreement is within 10 percent. Thus the method illustrated in figure 12 provides a means for predicting the initial current for different RC time constant circuits, as applied to a melting Manganin wire.

It is apparent from figure 12 that for probable end-of-melt points at $k \geq 8$, the initial current required is insensitive to the value of RC chosen. This fact can be used to define the design parameters for a first estimate of the capacitance required for a Manganin-wire ignition system. The system current can be treated as a constant and divides equally into each wire. Also the assumption is made that the electrical energy from the capacitor bank is equal to the calculated thermal energy necessary to reach the end-of-melt point. (From the multiple-wire jig test, the calculated thermal energy was found to be within 16 percent of the measured electrical energy required to reach the probable end-of-melt point for Manganin wire.) Defining the energy discharge from the capacitor storage as $(C/2)(V_o^2 - V_f^2)$ where

$$V_f = V_o e^{-(1/R_L C)t_R}$$

and using a series expansion of $1/(1+x)$ for e^{-x} gives a first-order approximation for the capacitance:

$$C = \frac{-2W_T}{R_L \left(n^2 I_o^2 R_L - \frac{W_T}{t_R} \right)} \quad (\text{farads}) \quad (6)$$

The capacitance calculated from equation (6) represents a maximum value required for the wire-melting process, since it is predicated on a step-function type of current pulse. If "on-hand" capacitors are to be used for an ignition system, the calculated value of capacitance can be reduced and matched to the required voltage as determined from figure 12. Since this is the limiting case, the effect on the required initial current density will be small.

Although the present method has been applied to Manganin wire only, some conclusions can be drawn if the action integral value of this material is compared with that of other materials. For example, the value for copper is $93 \times 10^{-3} \text{ A} \cdot \text{C}/(\text{cir. mils})^2$ (determined from ref. 8) and for Manganin it is 3.75×10^{-3} , as shown in figure 10. The difference results from the widely different value of resistivity for the two materials, copper being 10.37 and Manganin 290 ohms per cir. mil-foot. From equation (5), it can be shown that the initial current required for melting the copper wire would be close to 10 times that required for Manganin in an identical capacitor network. Currents of this magnitude can produce appreciable ohmic heating effects in the leads connecting the capacitor to the ignition wire system. Thus, high-resistivity materials tend to provide a better ignition system in terms of

power efficiency as well as minimizing the resistance-temperature effects on the RC time constant. Therefore, the present method is restricted to high-resistivity materials.

The foregoing method has been applied to the Ames facility operation and the driver has performed hundreds of consecutive, smooth combustion cycles of operation.

CONCLUDING REMARKS

Studies were made of a multiwire system for igniting a hydrogen-oxygen-helium mixture in the combustion driver of the Ames 1-foot shock tunnel. Detonation-free combustion of a large volume of gas at an initial pressure of 50 atmospheres can result if the wires are impulsively heated by an appropriate amount of electrical energy. Both the amount of energy and the rate at which it is released are determined by the wire size and material properties, as well as by the requirement that the wire must melt uniformly.

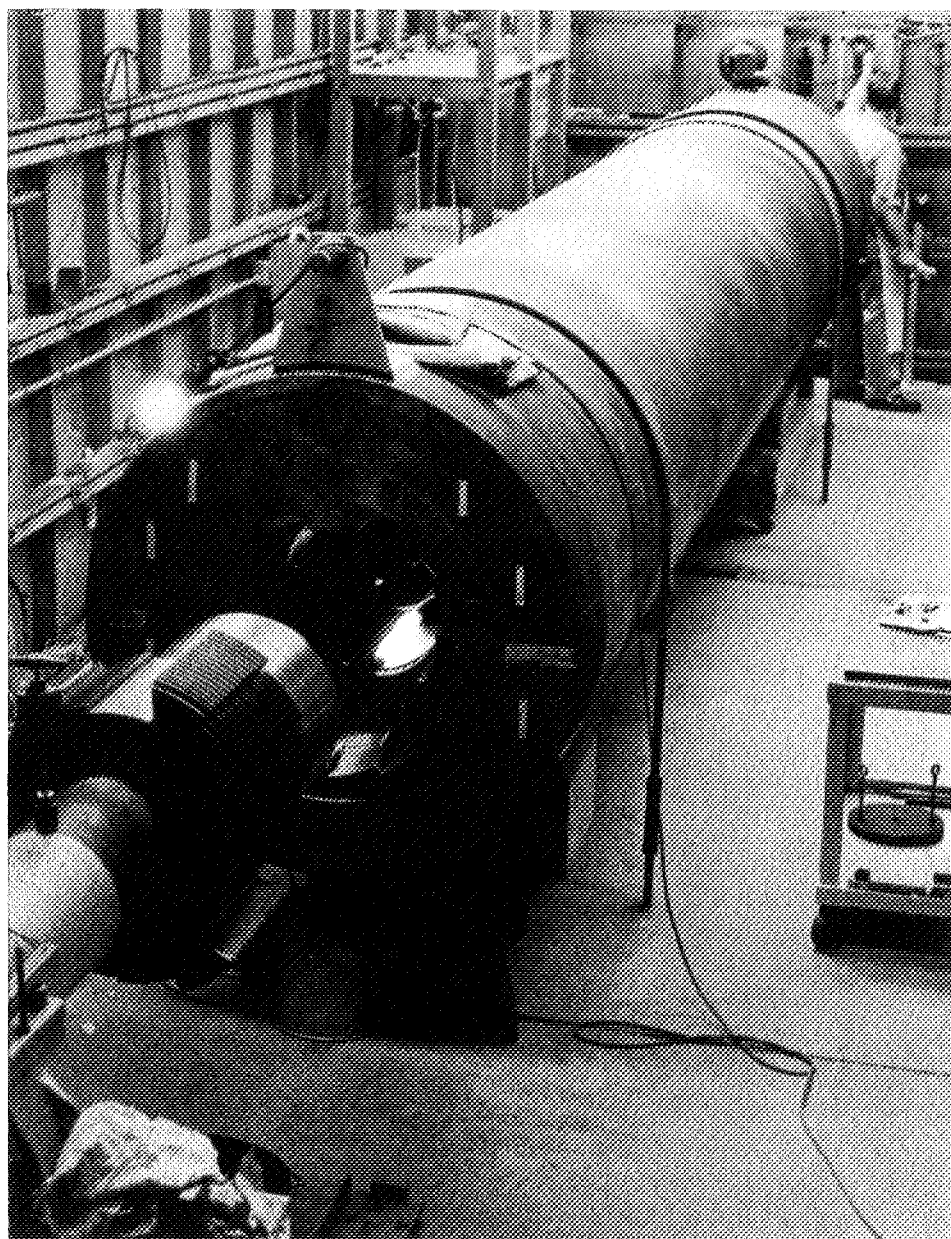
A semiempirical method based on the "action integral" concept of Anderson and Neilson has been developed for calculating the energy required for properly melting the wire in a reacting gas environment. The results of this method compare favorably with the experimental data over a substantial range of initial currents.

Ames Research Center

National Aeronautics and Space Administration
Moffett Field, Calif., August 10, 1965

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Figure 1.- Combustion driver of the Ames 1-foot shock tunnel.

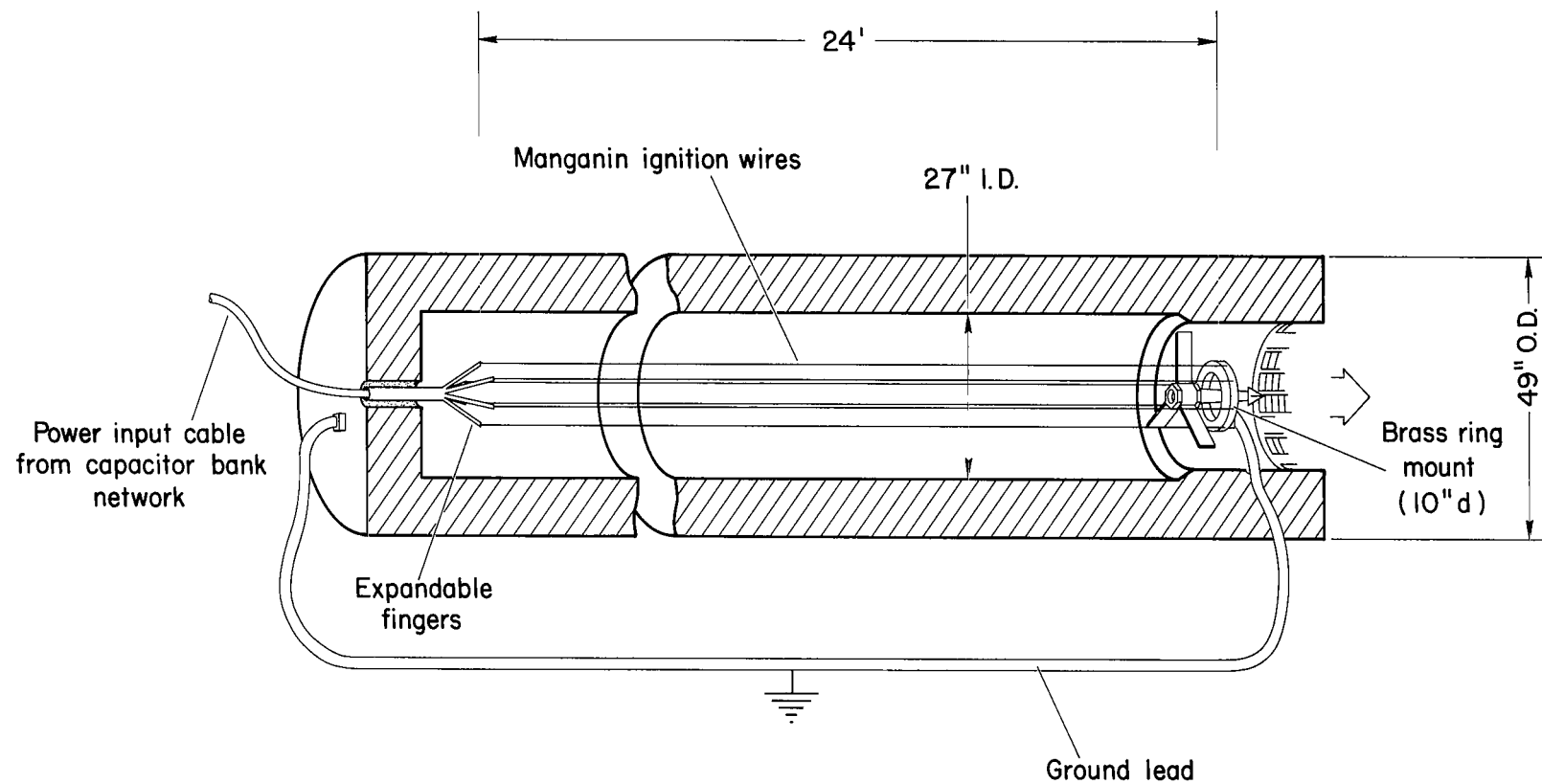


Figure 2.- Schematic drawing of the combustion chamber with ignition wires installed.

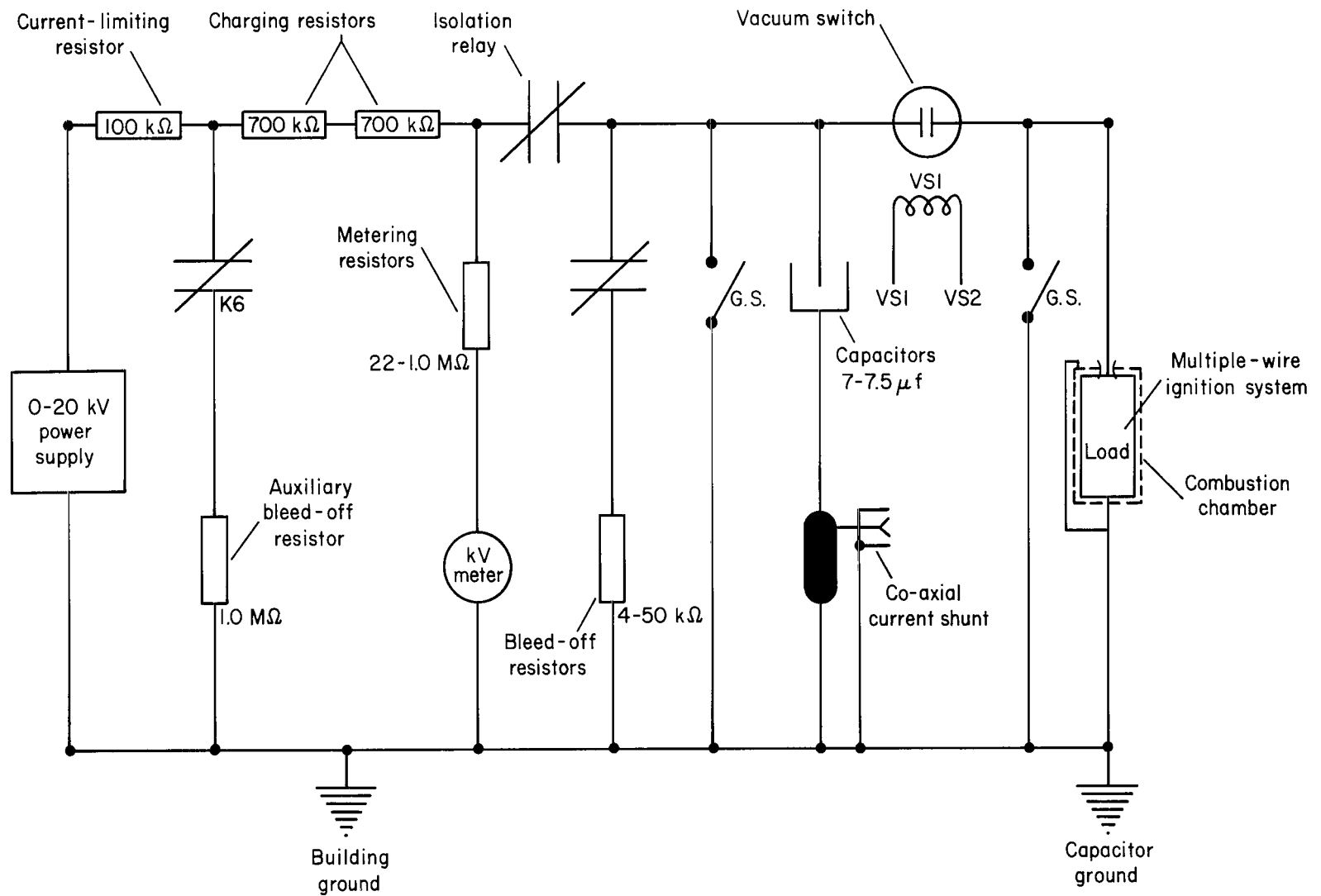


Figure 3.- Diagram of capacitor charge-discharge network.

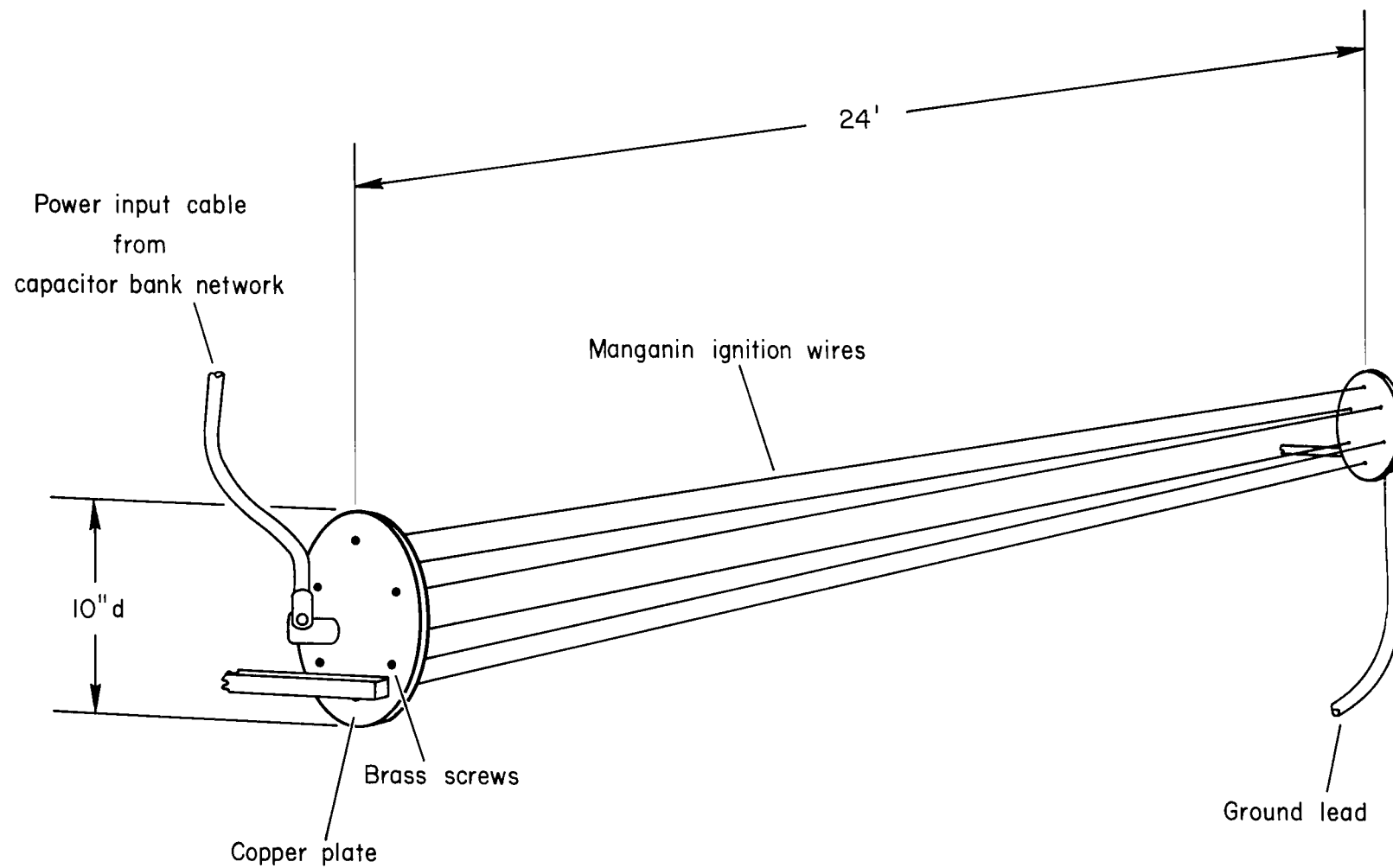
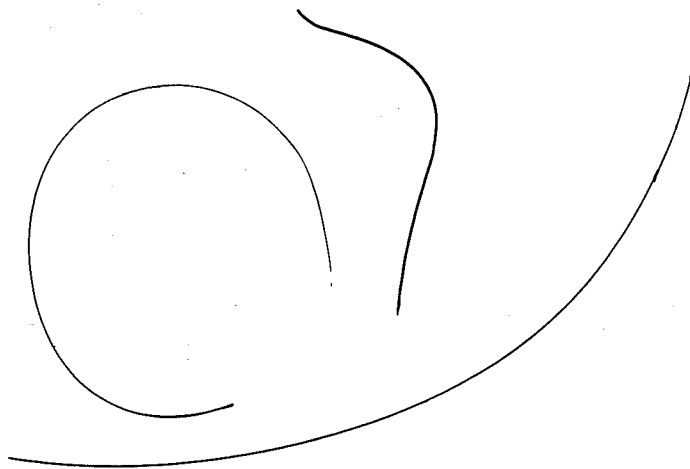
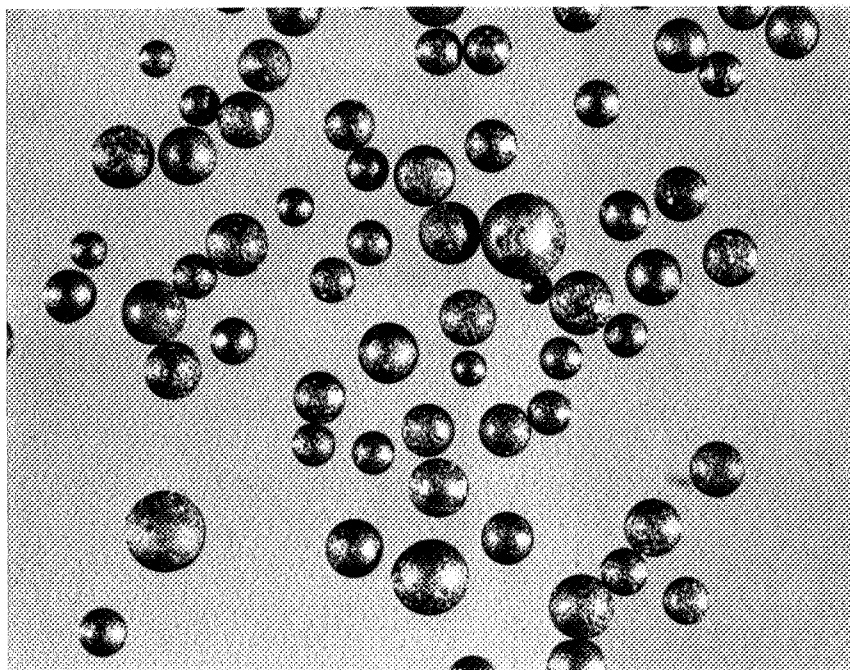


Figure 4.- Schematic drawing of multiple-wire test jig.



(a) $V_0 = 15$ kV; segments (4 times actual size).



(b) $V_0 = 17$ kV; spherical residue (62 times actual size).

Figure 5.- Typical wire residue after melting process.

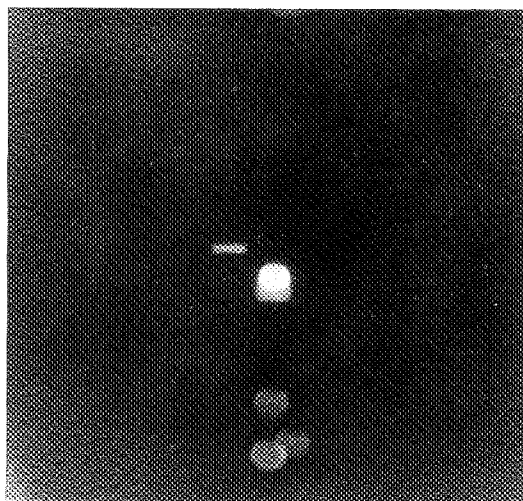
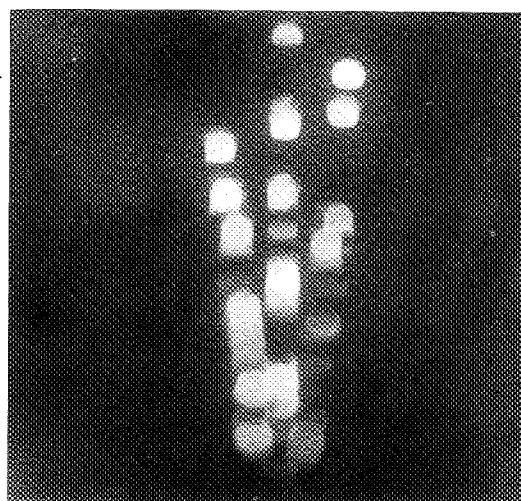
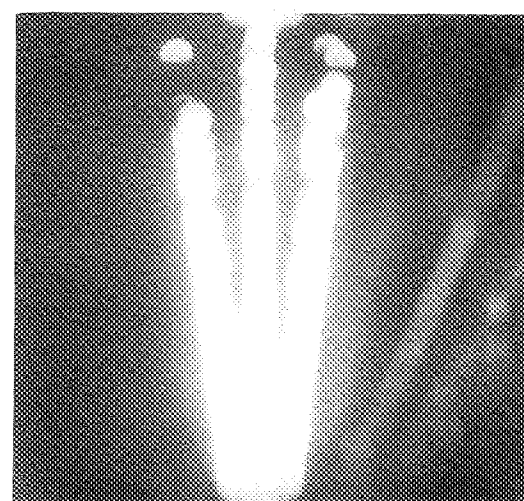
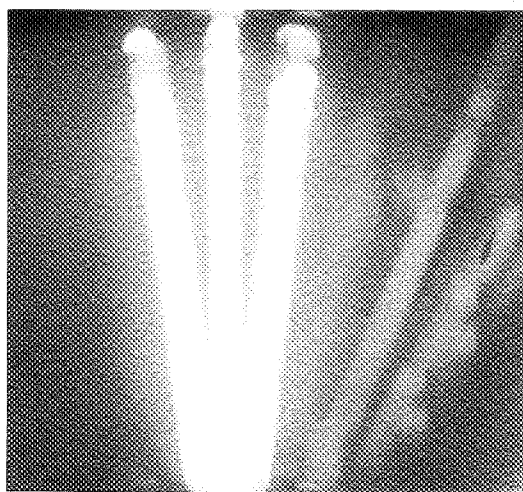
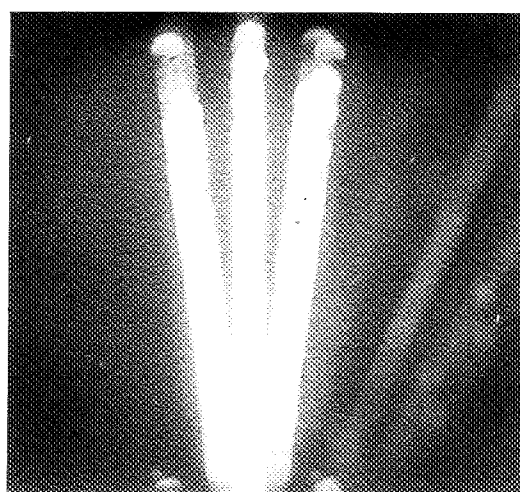
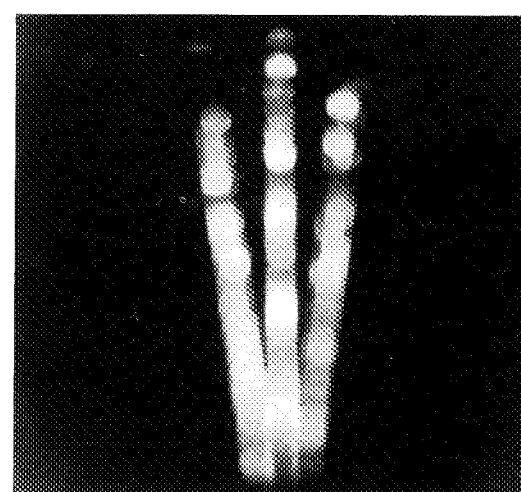
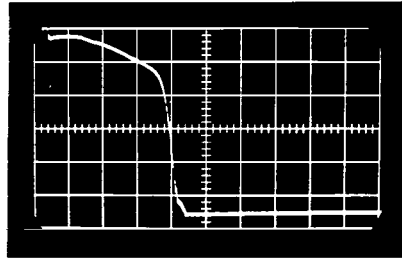
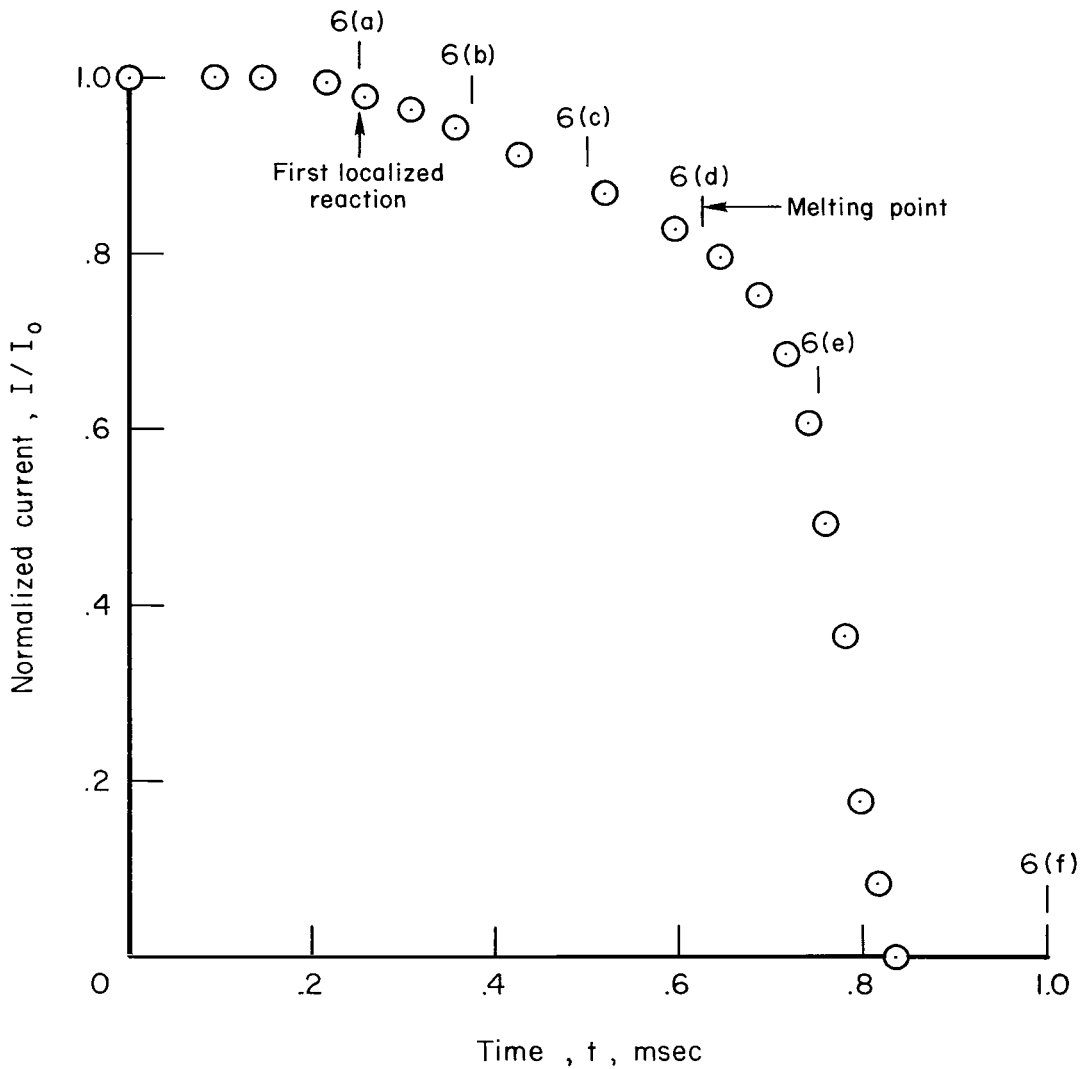
(a) $t = 0.250$ msec(b) $t = 0.375$ msec(c) $t = 0.500$ msec(d) $t = 0.625$ msec(e) $t = 0.750$ msec(f) $t = 1.00$ msec

Figure 6.- Photographs illustrating the melting of the Manganin wire set; 8000 frames/sec, $V_0 = 17$ kV.

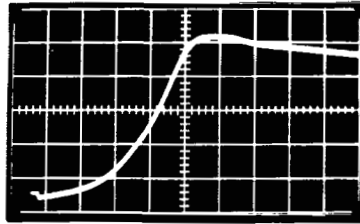


(a) Typical current record (right to left).

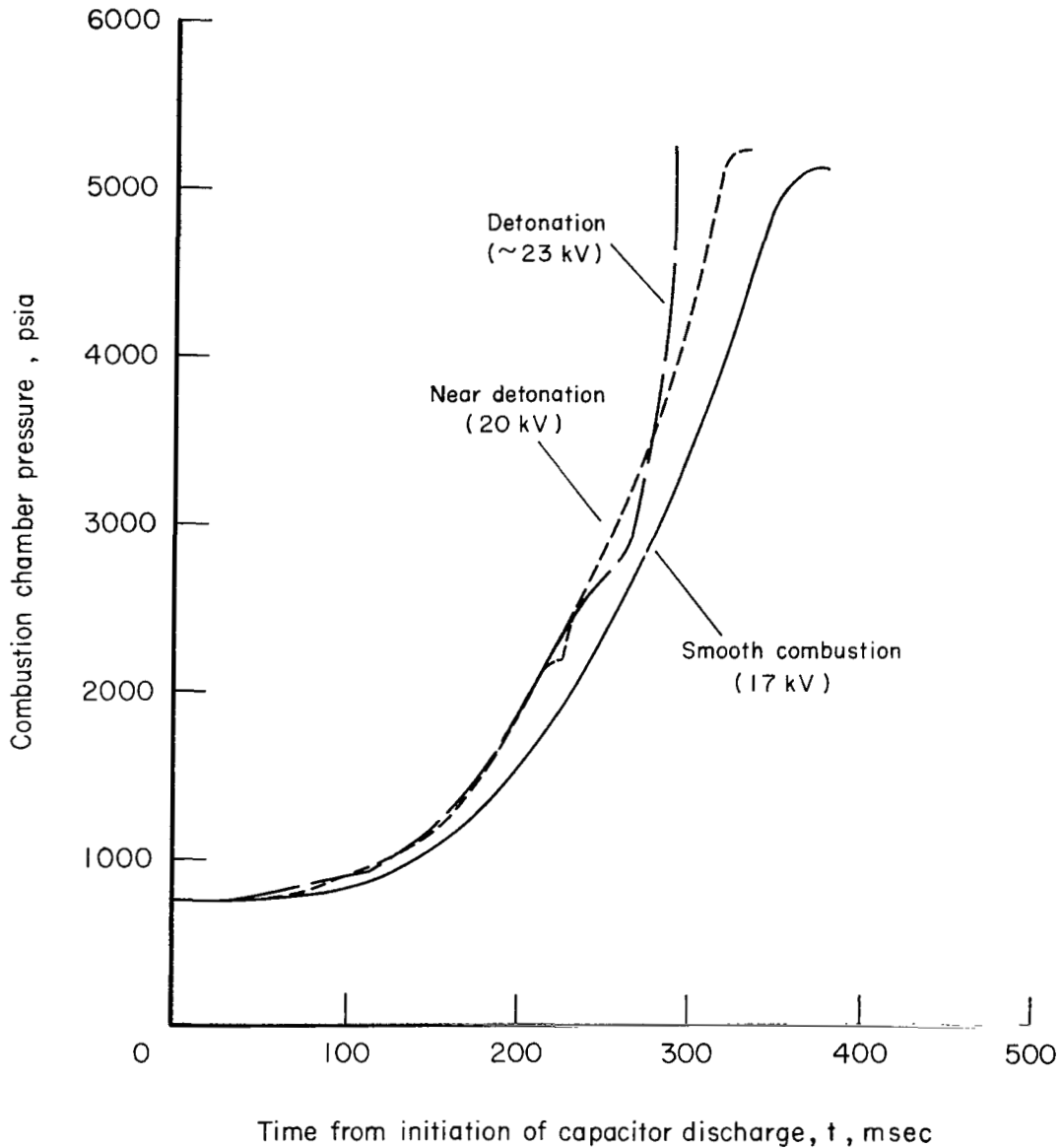


(b) Normalized current record (numbers refer to photographs shown in fig. 5).

Figure 7.- Current-time history for $V_0 = 17$ kV.



(a) Typical smooth combustion at 17 kV, vertical scale, 1100 psia/div and horizontal scale 100 msec/div.



(b) Combustion-pressure histories for initial voltages of 17, 20, and 23 kV.

Figure 8.- Combustion-pressure recorders from Ames 1-foot shock-tunnel driver.

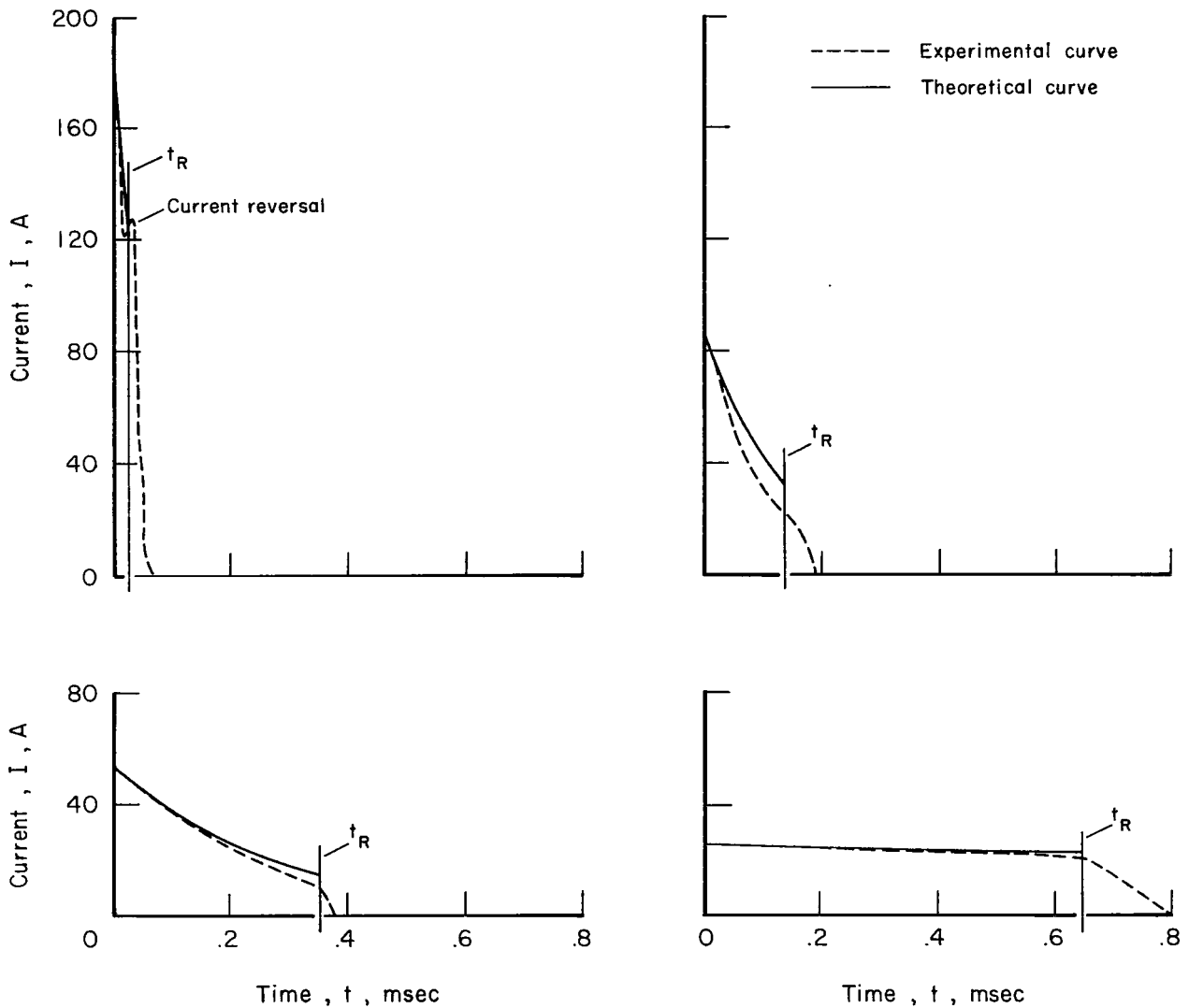


Figure 9.- Comparison of calculated and measured current-time histories for wire lengths of from 0.50 to 24 feet.

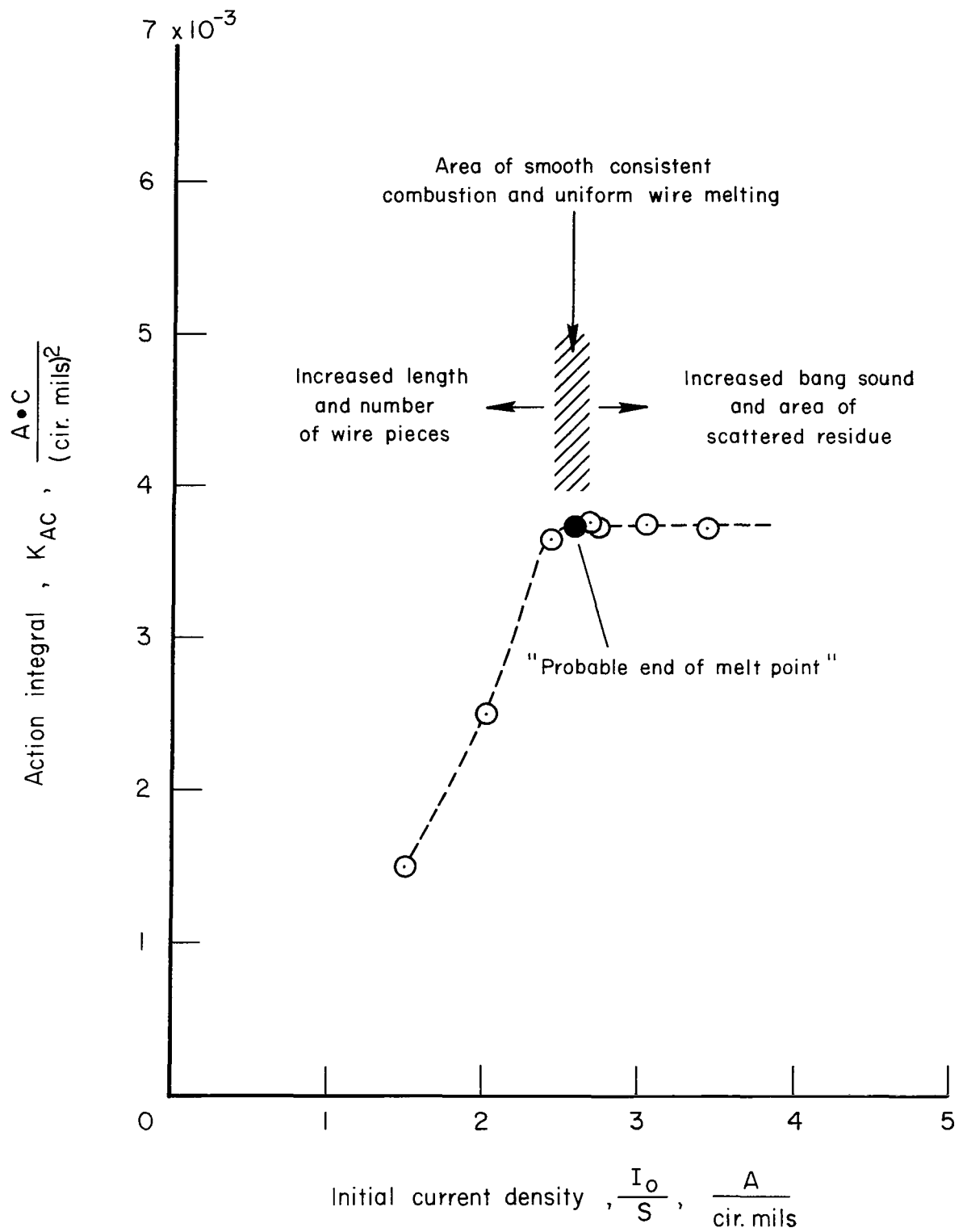


Figure 10.- Action integral values from the wire melting study;
 $R_{LC} = 5.98 \text{ msec.}$

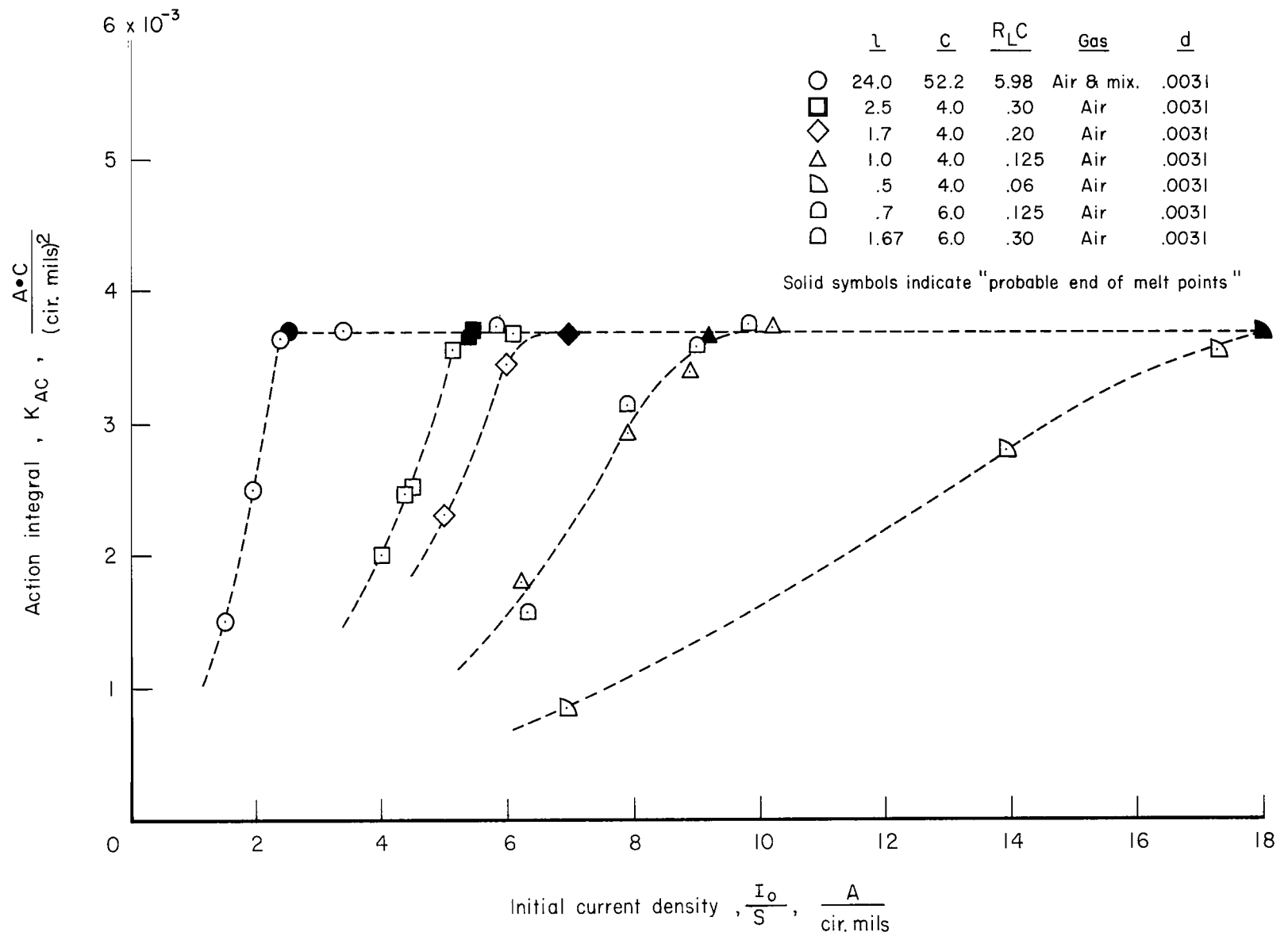


Figure 11.- Action integral as a function of initial current density.

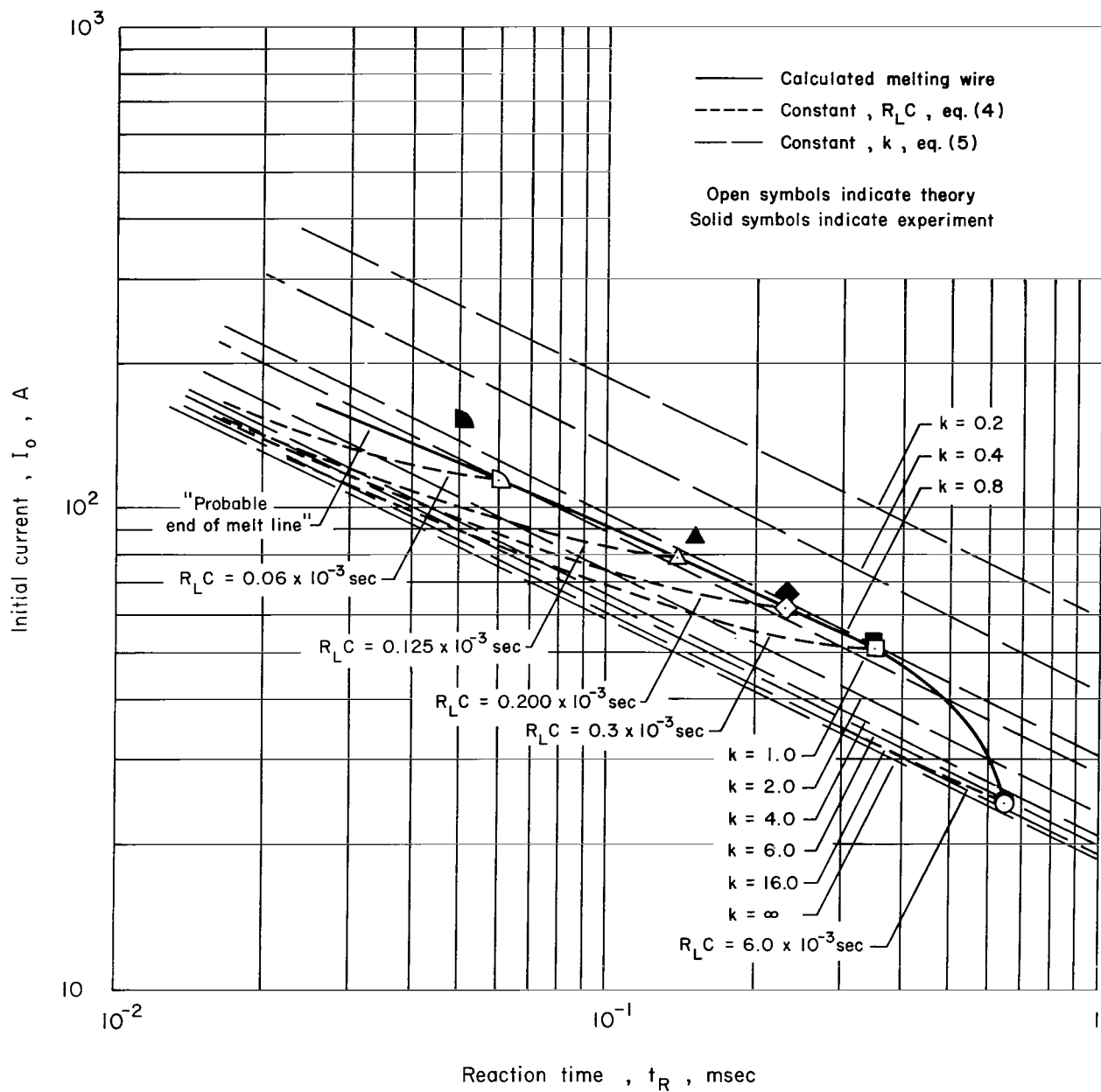


Figure 12.- Illustration of semiempirical method relating the action integral to initial current and reaction time (single wire).

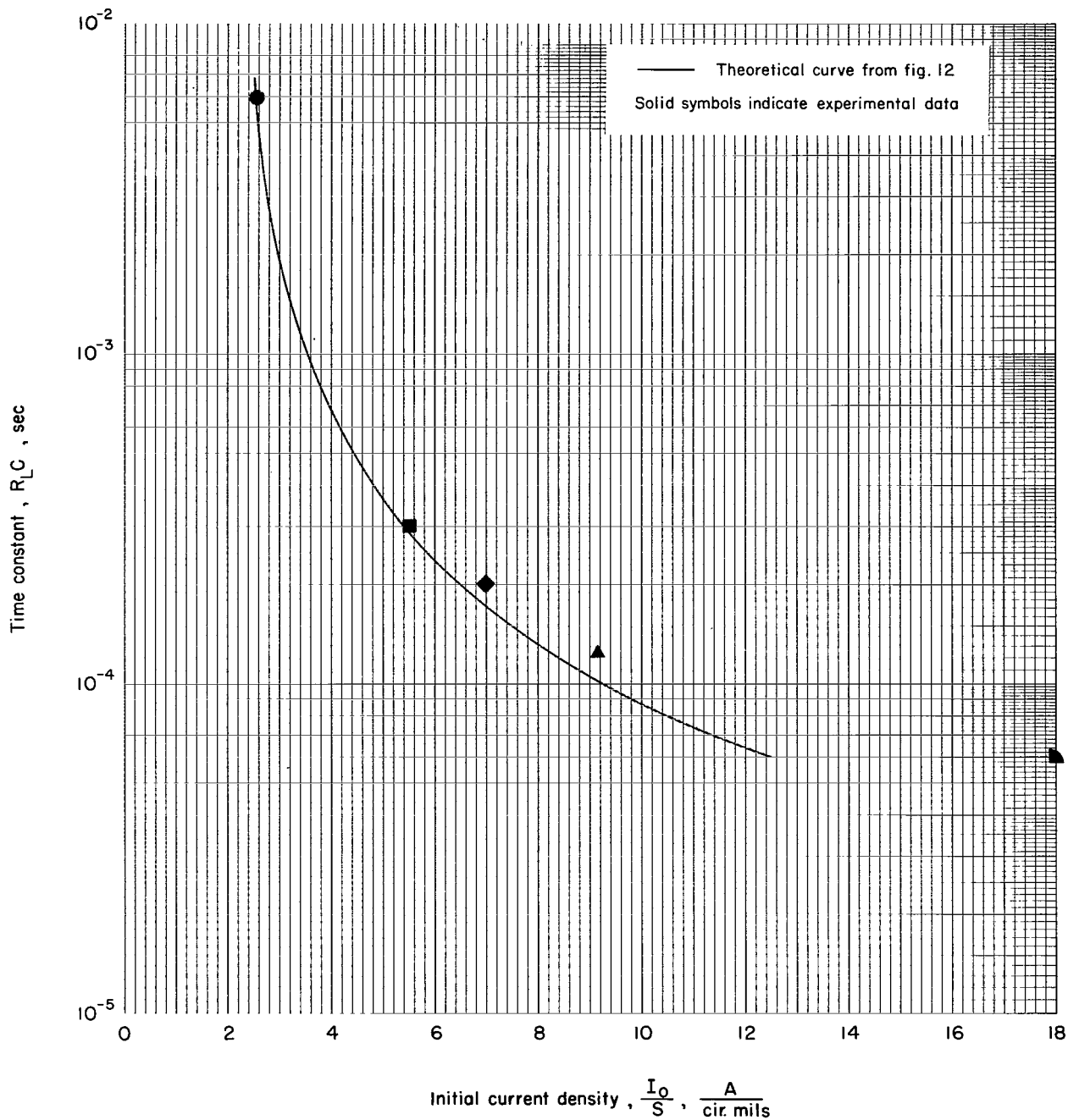


Figure 13.- The probable end-of-melt line in terms of the circuit time constant ($(I_0/S)_{\min}$ for $K_{AC} = \text{const.}$).

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